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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

The use of micrometeorological data to identify significant variables in evapotranspiration modeling

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Abstract

Because of the crucial role that plays in the hydrological water balance, evapotranspiration estimation has always represented a field of substantial and continuous scientific application. Evapotranspiration fluxes are however and objectively difficult to be measured and predicted. Many different models have then been reported in the related literature, which are able to quantify the evapotranspiration process starting from a more or less reduced database of empirical data. The present paper aims at the comparison between models of maximum crop and actual evapotranspiration (ET_0) applied to an eddy covariance micrometeorological tower located in Southern Italy. In particular, the Penman-Monteith model, in the simplified version proposal of FAO, and the model of Priestley-Taylor, have been herein considered. On a daily time scale of aggregation, both examined models have good capacity in the estimation of evapotranspiration fluxes. Using a database input of daily average air temperatures and analytically calculating the other relevant parameters, both the simplified method proposed by FAO Penman-Monteith and the Priestley-Taylor model show a comparable fit to the observed data, with a similar over-prediction of about respectively 17% and 14%.

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Keywords: reference evapotranspiration; actual evapotranspiration, Penman-Monteith, Priestley-Taylor, eddy covariance.

1. Introduction

The assessment of the evapotranspiration component of the water cycle assumes a very important role for water resources management, weather forecasts processing and local to global climate models. Simulation is also a field of large scientific applications, given the great difficulties in direct and

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continuous measurement of evapotranspiration fluxes, especially with changes in spatial and temporal scales. Because of these difficulties, a number of models, more or less robust, have been proposed in the scientific literature, able to directly relate the evapotranspiration process to more readily and easily available climate variable, taking advantage of its dependence on the available water content, the topography and the processes of energy and masses exchange the soil-vegetation-atmosphere system, linking the water cycle to the energy fluxes cycle.

The model that has been shown to have the higher reliability and accuracy in simulating the evapotranspiration dynamic is the Penman-Monteith [1,2] able to take into account not only the energy forcing surface, but also the phenomena of crop resistance and aerodynamic features. By contrast, as a drawback, such a formulation requires a rather time consuming database of variable to be monitored for a particular field, besides the simple climate variables. The scientific community has developed than formulations, of the same simplified model, able to meet the deficit between required and available records, through additional data and modeling approximations, which have been widely validated[3].

The widespread use and the rather high prediction reliability have made this model as a reference approach in comparative studies [4]. The Priestley-Taylor model [5], which represent a simplification of the Penman-Monteith model, removing the aerodynamic resistance component, is a further well-known and widely used approach to assess maximum crop evapotranspiration fluxes [6-10]. The predictive capabilities of the latter approach, of a more simple and rapid application, appear to be not always satisfactory, probably also due to a specific condition of climate and vegetation that make the model unsuitable in particular sites. The rapid diffusion in monitoring micrometeorological variables instrumentation and the eddy covariance technique can moreover provide estimates of actual evapotranspiration, also at the high temporal resolution necessary to examine processes. Peculiarity, pros and cons of the method are stressed in Wilson et al. [11].

This paper aims at the assessment of three empirical models oriented at the estimation of maximum crop evapotranspiration fluxes, the Penman-Monteith, the Priestly-Taylor and the Thornthwaite model, and in their comparison with eddy correlation actual evapotranspiration fluxes, measured at a particular site located in Southern Italy, experiencing a typical Mediterranean climate, with dry summers and wet winters seasons. In a context of data scarcity, the empirical models operate under a number of simplification and simulate the process dynamic based on a very limited data set, consisting of minimum and maximum daily air temperature records. Consistency of estimates between each of the techniques is investigated and comparison on different time scale, from daily to monthly, are also given in the following.

2. Reference evapotranspiration modeling

Three different models have been tested in this study to calculate maximum crop evapotranspiration fluxes. These are the Penman-Monteith (FAO-PM), the Priestley-Taylor and the Thornthwaite models. Even though the last approach is generally referred to in case of potential evapotranspiration assessment, the coincidence between the reference crop, as defined by the FAO, and the monitored field site vegetation type, the three models can be referred as to be all algorithm for the estimation of the same process.

The Penman-Monteith model expanded over the Penman model, considering maximum crop evapotranspiration rate as a combination of mass and surface energy balance and introducing the concepts of canopy and aerodynamic resistances. As in the FAO formulation, reference crop is a short, uniform and well watered green plant cover, and the corresponding evapotranspiration rate ET_0 (mm/d) is:

$$ET_0 = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where Rn is the net solar radiation (MJ m⁻² d⁻¹), G is the soil heat flux (MJ m⁻² d⁻¹), T is the average daily air temperature (°C), u_2 is the wind speed at two meters above the soil surface (m/s), e_s the saturation vapor pressure (Pa), e_a the actual vapor pressure (Pa), Δ is the slope of the saturation-to-vapor-pressure curve (Pa °C⁻¹), and γ the psychrometric constant (kPa °C⁻¹). It clearly appears that the application of equation (1) require a large number of observations and measurement, frequently not available. The Authors themselves suggested some simplifications to the formula, setting up a number of relations that allow the estimation of reference evapotranspiration rate starting only from the knowledge of daily maximum and minimum data.

The Priestly-Taylor model proposed a simplification of the Penman-Monteith model, removing the aerodynamic resistance component and introducing a correction coefficient k , for which calibration is necessary:

$$ET_0 = k \frac{\Delta}{\Delta + \gamma} \frac{Rn - G}{\lambda} \quad (2)$$

where all terms are as in equation (1). Priestley-Taylor found a value of 1.26 for the coefficient k , in case of well-watered vegetated areas. The Priestly-Taylor model can take advantage of the same simplification assumed for the Penman-Monteith, making the mean daily air temperature the basic monitored variable needed for reference evapotranspiration rate assessment.

On a monthly time scale, maximum potential ET can be also assessed with reference to the Thornthwaite method. The Thornthwaite method is based on an empirical exponential relationship between potential evapotranspiration and mean air temperature:

$$ET_{0j} = k_j \cdot 16.2 \left(\frac{10 \cdot t_j}{I} \right)^a \quad (3)$$

and evaluates ET_{0j} potential evapotranspiration on monthly scale (in mm) simply requiring the monthly average temperature t_j (in °C). The thermal index I and the empirical exponent a are in fact respectively functions of t_j and I itself.

3. Site description, instruments and measurements

Observation data analyzed in this study have been collected in Fisciano (SA), Campania region, Southern Italy, (40°46'0"N, 14°48'0"E, 320m above sea level), from May 2008 until April 2011 (Fig.1). The Eddy Covariance tower is located in a property area of Salerno University Campus, in a grass field, approximately flat, with sparse vegetation, respecting the fetch height ratio of 100 in all main fluxes directions. The station is equipped with several instruments to measure eddy covariance fluxes and all components of energy balance: sonic anemometer CSAT-3 (Campbell Scientific) for wind speed components and sonic temperature fluctuations measurements installed at 3 m above the soil

surface, open-pathinfrared gas analyzer H₂O/CO₂ LI-7500, LiCorSci., for water and carbon vaporfluctuations measurements, net radiometer NR-LITE, Kipp&Zonen,for net radiation measurements, 2 self-calibrating heat flux sensors HFP01SC installed at 3 m above the soil surface, Hukseflux, placed 10 cm under soil surface to measure heat flux absorbed by the soil and, finally, in correspondence of each soil heat flux, there is a termocouple TCAV that measures the soil temperature respectively at 2 cm and 6 cm under the soil surface.

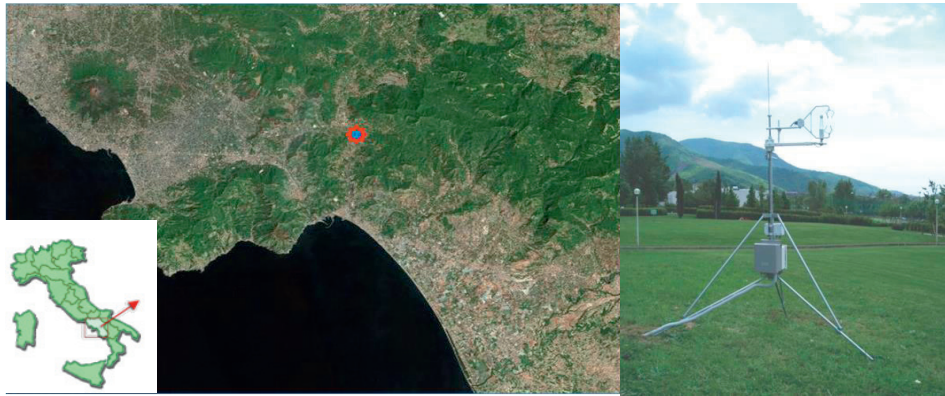


Fig. 1. The monitoring field site

Because of the turbulent fluctuations of data, sampling is made at a frequency of 10 Hz and averaged on periods varying from 10 to 60 minutes by a datalogger, CR1000 Campbell Scientific, also programmed for the acquisition and the statistic elaboration of low frequency meteorological data (slow-data 1 Hz). Energy power is assured by 2x100 W solar panel witch recharge 2 parallel-connected 105 Ah/12V batteries with recharge regulators.

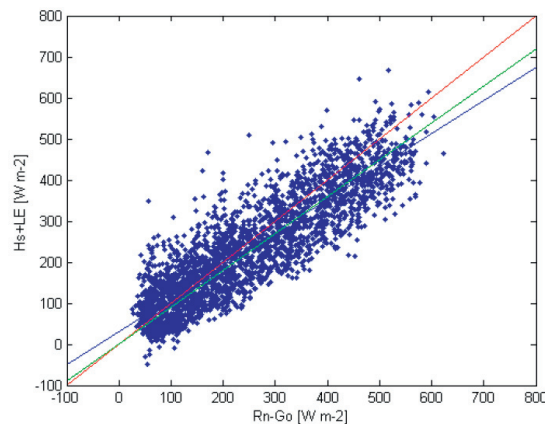


Fig. 2. Energy balance closure: the blue line is the least square regression line, the green line is regression line with null intercept, the red line is the 1:1 line.

Observed data have been processed for errors corrections: coordinates rotations, linear detrending [12,13], sonic temperature correction, Webb-Pearman-Leuning filtering [14], stationarity tests. The station footprint, evaluated using the Schuepp model [15], is about 100 m. In order to evaluate the reliability of the Eddy Covariance measurements, the standard energy balance closure was considered: ordinary least square regression provides a closure of about 80% during the whole year and of about 90% during the period from April to October (Fig. 2). The lack of energy balance closure, well documented in the scientific literature, has been distributed over the radiative energy fluxes, keeping a constant value of the Bowen ratio [16]. In the end aggregation from instantaneous time scale to daily time scale has been performed as a simple average over the daily time window and as through the evaporative fraction [17-19]. More details for the experimental site are given in Casola et al. [20].

4. Experimental data analysis and model comparisons

Evapotranspiration fluxes are strongly driven by two main controls, the water availability (depending on soil water balance) and soil water abstraction atmosphere power (climate control). The proportion by which the two factors contribute to the evapotranspiration is a variable linked to the average climate regime of the area under examination. The experimental plot under investigation is characterized by a typical Mediterranean climate, featured by the existence of two distinct seasons: a winter season with low air temperatures and high rainfall rate, and a summer season with high air temperature and scarce to null rainfall rate. The repeated change between the seasons, as demonstrated by experimental evidence conducted in the same observation site results in a large soil water availability during the winter period and in a moderate to small soil water availability during the summer period, with rather long stationarity periods, alternating with periods of more or less abrupt transition [20-24]. In such a climate and hydrological regime, it would be expected, therefore, that evapotranspiration fluxes are limited by the lack of soil water content during the dry and hot season, and by the evaporative atmosphere power during the rainy and cold season. On a modeling point of view, these controls would be described by different significant variables to be accounted for, on a seasonal base, to predict evapotranspiration rates.

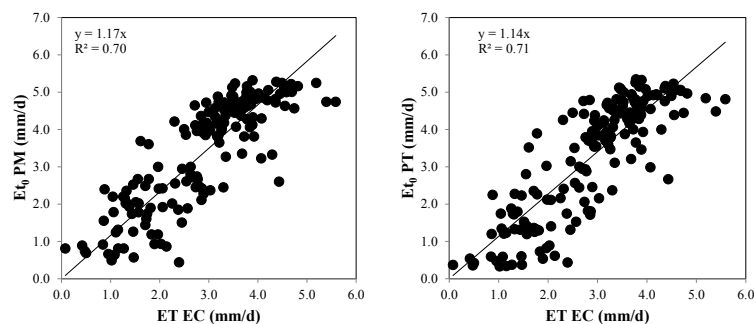


Fig. 3. Relationship between Penman-Monteith (PM), Priestley-Taylor (PT) and eddy correlation (EC) estimates of evapotranspiration at the daily scale.

The daily evapotranspiration estimates from Penman-Monteith (PM), Priestley-Taylor (PT) and eddy covariance (EC) methods are shown for the period May 2008 – May 2009 in Fig. 3.

The one-to-one correspondence between observed evapotranspiration daily rates (EC) and modeled rates (PM and PT) appear satisfactory and above all comparable, as showed by the goodness-of-fit statistics given in Table 1. Both models predict a larger evapotranspiration rate, of about 17% in case of

PM model and of 14% in case of PT model, compared to EC technique. This is essentially caused by the different variables that actually EC, on one side, and PM and PT, on the other side, would represent. In fact, whilst EC would consider the actual evapotranspiration fluxes, PM and PT approaches would represent the potential evapotranspiration fluxes, generally larger than the actual fluxes because accounting for a well-watered limited condition. In the case of eddy correlation measurement, only no rainy days have been accounted in the analysis, because the occurrences of precipitation could alter measurements significance. Inclusion of all daily data, both rainy and no rainy days, would reduce the correlation coefficient to 0.52 and 0.57 respectively for the PM and PT models.

Table 1. Regression prediction models performances.

ET model	MAE (mm)	MSE (mm ²)	RMSE (mm)	bias (%)	R ²
PM	0.806	0.878	0.937	18.44	0.70
PT	0.797	0.879	0.937	18.80	0.71

Observed and modeled rates shows however an overestimation for ET values larger than about 3 mm/d. These conditions would typically occur during the hot and dry season, from May to August, when modeled potential rate, driven by the quite high daily temperature, over-predict actual rates, perhaps mainly driven by the soil water content availability, obviously limited in the investigated plot during this particular season.

Because of a number of applications coherent with large time scale aggregation, comparison are also further given at the monthly, seasonal and annual scale. The Thornthwaite (TH) method estimates have also been considered at these time scales. Monthly and seasonal rates are represented in the following Fig.4.

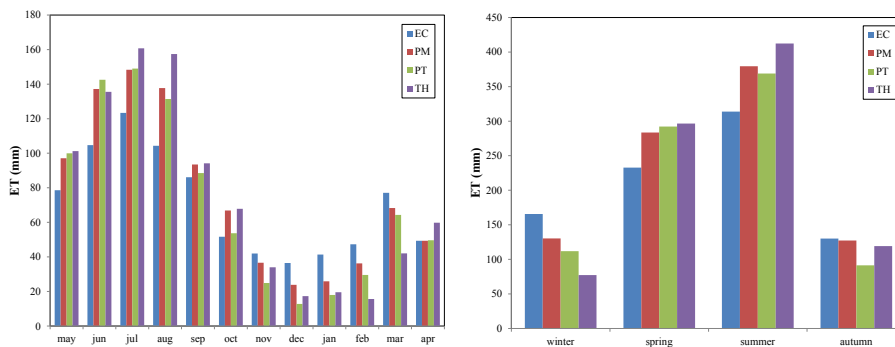


Fig. 4. Penman-Monteith (PM), Priestley-Taylor (PT); Thornthwaite (TH) and eddy correlation (EC) monthly and seasonal estimates comparison.

According to the pattern illustrated in Fig. 3, an overestimation and an underestimation are also clearly visible at the monthly scale, respectively during the summer and winter seasons. At the annual scale, see Table 2, the PT approach seems to be the most suitable, with a relative error of 3% over observed EC rate. PM and TH methods relative errors are respectively of about 9% and 7% over observed EC rates.

Table 2. Annual evapotranspiration rates comparison.

ET PM (mm)	ET PT (mm)	ET TH (mm)	ET EC (mm)
921	864	905	842

5. Conclusions

This paper has presented an experimental study in which the use of micrometeorological eddy covariance data gives useful insights to identify significant variables in evapotranspiration modeling at various time scale aggregations. Eddy correlation measurements have been assumed as the observed actual evapotranspiration fluxes and the Penman-Monteith and Priestley-Taylor models have been used to reproduce evapotranspiration patterns dynamics at the experimental plot scale, using simple and poor data requiring formulation. Models applications only required minimum and maximum daily temperature and no further calibration has been conducted. Comparisons between investigated approaches demonstrate that there is a good correspondence in evapotranspiration observed versus modeled rates, especially at coarse time scale, from seasonal to annual. Patterns dynamics comparison at the daily time scale also indicate a good agreement between observed and modeled data, with an evident overestimation detected during a particular period of the year, corresponding to the summer season. In fact, during the hot and dry season, from May to August, modeled potential rate, driven by the quite high daily temperature, over-predict actual rates, perhaps mainly driven by the soil water content availability, obviously limited in the investigated plot during this particular season. PM and PT perform almost the same, with a similar over-prediction of about 17% in case of PM model and of 14% in case of PT model, and with a moderate advantage of PT over PM, considering the annual time scale. Air temperature can thus be identified as the main variable in modeling the ET process at the experimental field site.

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